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MODEL A: HIGH-TEMPERATURE TRIBOMETER

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151 California Street
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A high temperature tribometer has been specifically designed and fabricated to accurately measure, in real time, friction and wear characteristics of materials at temperatures up to 1000°C in a controlled atmosphere. The instrument is capable of three-axis motion control, automated sample load, automated powder and liquid lubrication feed, and computer control of instrument and data acquisition. The tribometer can be run as a stand-alone using the front panels of the tribometer electronic control box or it can be run using the computer. Computer set points can be used as a safety device in case the set parameters go out of bounds.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

This is the final report for the High-Temperature Tribometer developed by Advanced Mechanical Technology, Incorporated (AMTI) for the Aero Propulsion and Power Directorate of the Wright Laboratory (WL) under contract number F33615-89-C-2971.

The High-Temperature Tribometer is specifically designed to accurately measure the friction and wear characteristics of materials at temperatures up to 1000 degrees Centigrade in a controlled atmosphere. The High-Temperature Tribometer has been designated Model A and is based upon several previous models which AMTI designed and built. In order to obtain the required performance and advanced features of the Model A, it was necessary to make some major design changes to these earlier models. These changes involved both the electrical and mechanical portions of the tribometer. A photograph of the complete machine is shown in Figure 1.

Specific goals of the project:

- Control of sample temperature to 1000 degrees Centigrade
- Accurate, dynamic measure of wear under typical operating conditions
- Three-axis control of sample motion
- Automated control of sample load
- Measurement of the frictional properties of the sample
- Automated control of both powder and liquid lubrication feed
- Computer control and data acquisition.

These goals are met by integrating a precise mechanical system with a powerful embedded microprocessor based control system.

All Tribometer functions may be controlled with either a computer or the Tribometer front panel. The computer communicates with the embedded microprocessor which controls all Tribometer functions and monitors all transducer inputs. Additionally, the Tribometer may be operated in a stand-alone configuration, where all functions are controlled from the front panels of the Tribometer electronic control box.

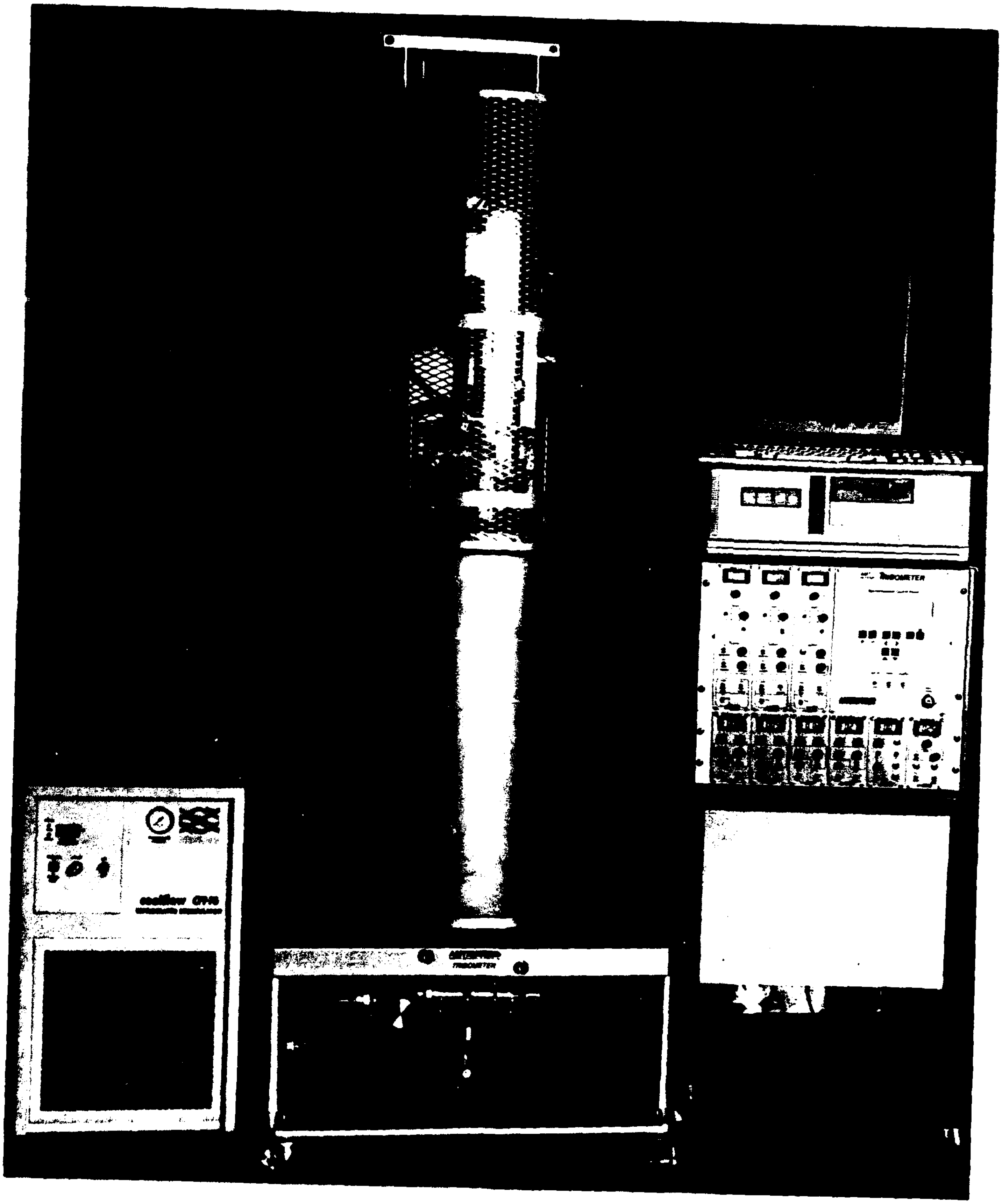


Figure 1. Photograph of Model A High-Temperature Tribometer

SYSTEM OVERVIEW

The High-Temperature Tribometer has the following capabilities:

- Motion in three axes
- Measurement of three orthogonal force vectors and one moment vector
- Automatic control of sample load
- Two methods of dynamic wear measurement
- Control of high-temperature furnace
- Automatic feeding of liquid and powder lubricants
- Automatic data collection
- Control of test chamber atmosphere.

These capabilities are supported by four major system elements:

- Mechanical control and transducer system
- Electrical power system
- Cooling system.
- Electronic control system.

Figure 2 shows a schematic representation of the four system elements.

The mechanical control system meets the demands of friction and wear testing under elevated temperatures in a controlled atmospheric environment. It consists of the following system elements:

- Drive trains for three axes
- Multi-axis force transducer
- Normal force loading module
- Wear transducers
- Lubrication feeders
- High-temperature furnace test chamber
- Vacuum/atmospheric control chamber.

The electrical power system supplies all electrical power. It consists of the following elements:

- Power supplies
- Power-distribution relays and fuses
- Servo amplifiers for motors
- Heater power system.

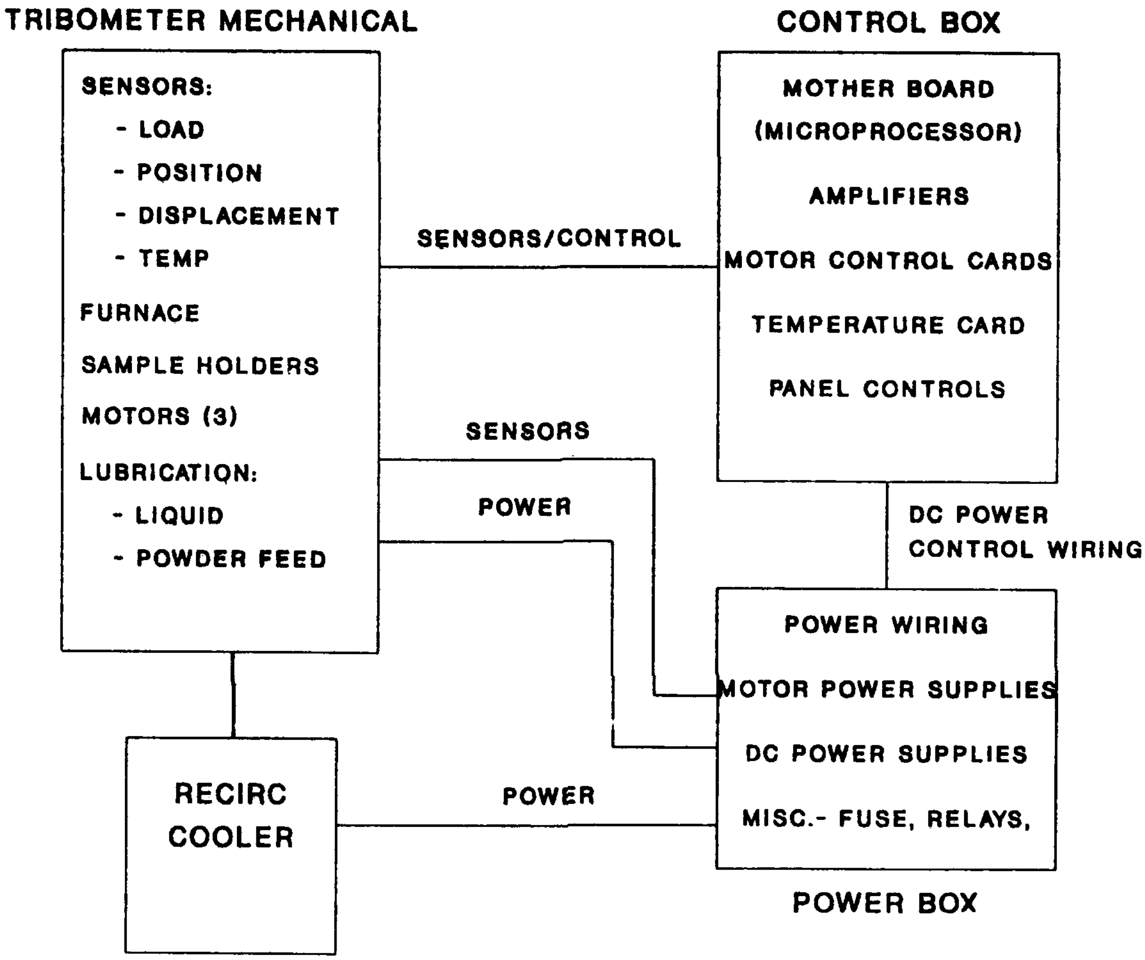


Figure 2. Schematic Overview of Tribometer

The cooling system maintains thermal equilibrium and protects temperature sensitive mechanical and transducer systems at high temperatures. The cooling system consists of the following elements:

- Recirculating bath chiller
- Tubing and passageways for coolant.

The electronic control system provides digital control of the entire Tribometer system (excluding the cooling system). It consists of the following elements:

- Microprocessor control panel
- Amplifiers for transducers
- Motor control modules
- Heater control module
- Tribometer mother-board.

MECHANICAL CONTROL AND TRANSDUCER SYSTEM

The Model A Tribometer is a three-axis friction and wear machine that supports many specimen sample configurations, including the common pin-on-disk test (ASTMG99-90).

The Model A Tribometer has two specimen holders. The lower specimen holder is mounted on a rotary spindle (the R-Axis) which rotates around the Z-axis. The upper specimen is inserted into a collet which is attached to a transducer head. This head transverse radially over the bottom sample along the Y-axis, changing the wear track radius.

The samples are loaded against each other with the vertical Z-axis drive train. This drive train moves the lower specimen up against the upper specimen. As the lower sample moves up against the upper sample, compliance in a spring mounted to the upper sample holder creates a wide range of sample loads.

As the lower specimen is raised the Z-axis drive train lifts the Tribometer test chamber around the sample. The test chamber consists of a high-temperature 1000-degree-Centigrade furnace and a powder and liquid lubricant feeder which injects lubricant through the top cover plate of the furnace.

During testing the following may be monitored by sensors located on the transducer module:

- Sample wear from two independent sensors
- Sample load and frictional forces.

Enclosing the entire system is a stainless steel and glass atmospheric control chamber that can be lowered around the test chamber. The chamber can be evacuated and then filled with a controlled atmosphere.

An isometric drawing of the Tribometer which shows the test chamber, drive trains, transducer module and atmosphere control chamber is shown in Figure 3. Descriptions of the balloon labels in Figure 3 are provided in Table 1.

Drive Trains

The drive trains of the Tribometer are designed to allow accurate positioning of test samples, while still maintaining the mechanical stiffness required for accurate measurement and control of sample loading and wear measurement.

The position of the three drive trains are controlled with DC servo motors. The position of each axis is monitored with separate optical encoders.

Rotation - R-Axis

The rotary spindle, or R-axis, motor is located below the lower specimen holder spindle. The motor is capable of spinning the spindle up to 1500 RPM or reciprocating the spindle at rates up to 5 Hertz over a 100-degree arc.

The R-axis has a resolution of 0.1 degrees and a continuous torque rating of 15 inch pounds.

Radius - Y-Axis

The Model A High-Temperature Tribometer has an electrically controlled wear track radius adjustment. Earlier tribometers required that this parameter be manually adjusted and no electrical indicator of the actual radius was provided. The Model A has full static and dynamic wear track radius adjustment with electrical position indication. The Y-axis controls the wear track radius of the upper specimen on the lower specimen by moving the transducer head orthogonally from the center of the lower specimen holder. The transducer head slides on two precision linear bearings. The head is driven by a backlash free harmonic drive and a preloaded acme screw.

The Y-axis has a travel of 1.25 inches with a resolution of 0.1 mils.

Z-Axis

The Z-axis controls the height of the lower specimen. The lower specimen holder and spindle travel on two pairs of linear bearings. A backlash free harmonic drive and an acme screw drive the assembly.

The Z-axis has a travel of 12 inches with a resolution of 0.1 mils.

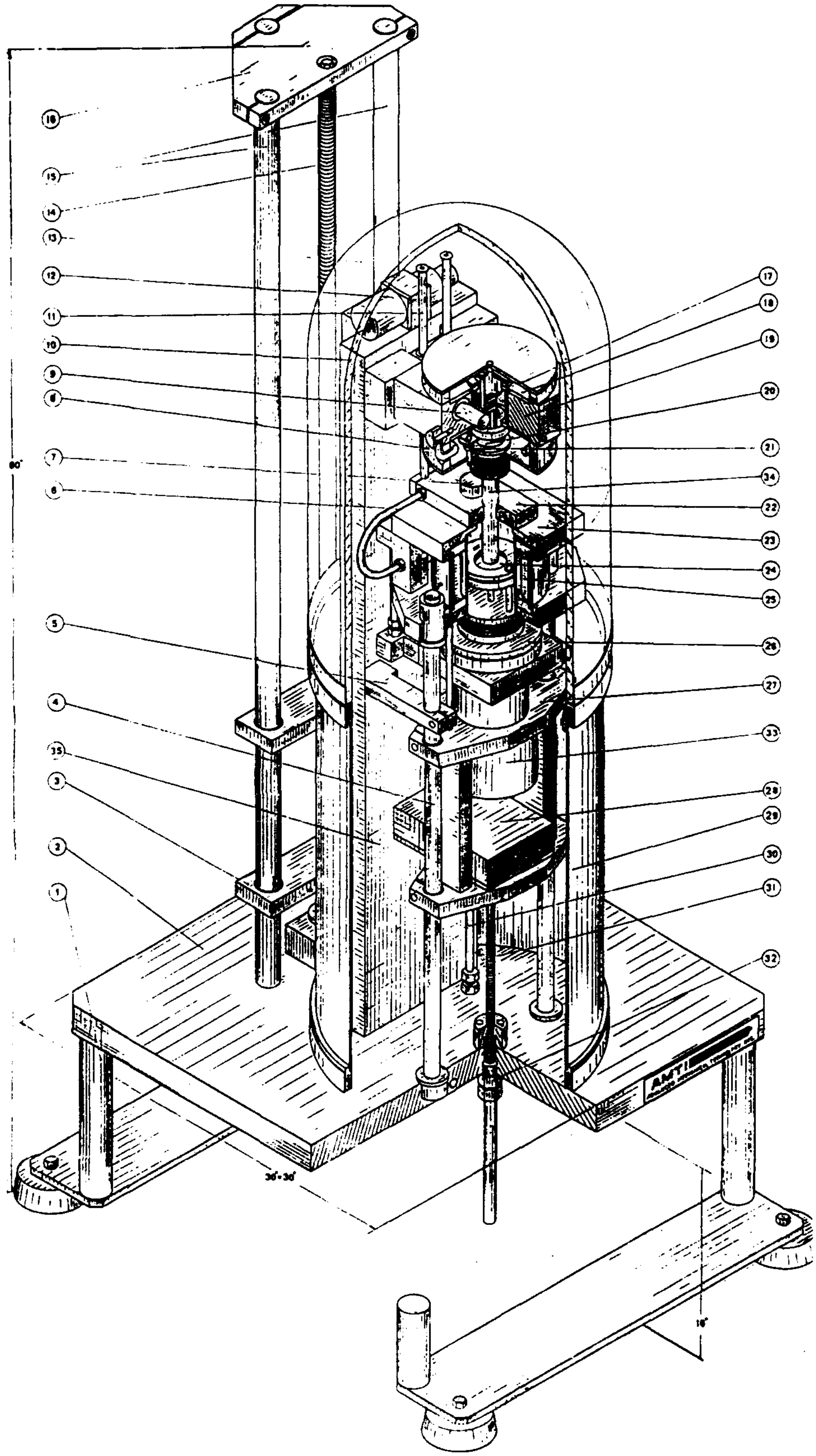


Figure 3. Isometric Drawing of Tribometer

TABLE 1. TRIBOMETER PARTS LIST

1. Support Leg (4)
2. Base Plate
3. Vacuum Enclosure Slide Bearing Mount (2)
4. Z-Axis Shaft (2)
5. Upper Z-Axis Shaft Support (2)
6. Flexible Cooling Line (2)
7. Powdered Lubricant Feed Unit
8. Cooling Passage
9. Y-Axis Slide Shaft (2)
10. Y-Axis Spacer Block (2)
11. Furnace Cover Plate Guide Shaft (2)
12. Liquid Lubricant Feed Unit
13. Glass Vacuum Bell Jar
14. Vacuum Enclosure Lead Screw
15. Vacuum Enclosure Slide Shafts (3)
16. Top Support Plate
17. Hall Effect Sensor
18. Diaphragm Spring (2)
19. Transducer Module Block
20. Multi-Axis Transducer Element
21. Suspension Magnet (2)
22. Furnace Cover Plate
23. Top Furnace Plate
24. Lower Specimen
25. Furnace Element
26. Spindle Unit
27. Spindle Motor Mounting Plate
28. Z-Axis Harmonic Drive Unit
29. Lower Stainless Steel Vacuum Enclosure
30. Telescopic Cooling Tube
31. Z-Axis Lead Screw
32. Z-Axis Lead Screw Cover Fitting
33. Spindle Motor
34. Upper Specimen Mount
35. Vertical Base Plate
36. Pneumatic Sensing Nozzle Electronics

Multi-Axis Force Transducer

The upper specimen holder is mounted directly to a multi-axis force transducer. This transducer is a special AMTI design that allows the accurate measurement of the dynamic forces occurring during friction and wear testing.

The transducer is a four component strain gauge load cell which senses the forces in the X, Y, and Z-axes (Fx, Fy, and Fz) and the moment around the Z axis (Mz). These four components allow the accurate calculation of the friction coefficients and forces for any arbitrary sliding motion of the test samples.

The maximum rated loads for this cell are:

Fx - 10 pounds
Fy - 10 pounds
Fz - 10 pounds
Mz - 20 inch-pounds.

Normal Force Loading System

The Model A Tribometer is designed to provide accurate, simple control of a wide range of sample loads in the normal direction. Sample load is provided by a pair of diaphragm springs in the transducer head. The Z-axis is used to deflect these springs and control the sample load.

The diaphragm springs provide frictionless compliance in the Z-axis while maintaining a high degree of stiffness in the X, Y, and Z-axes and stiffness to rotation about the Z-axis. Additionally, fluidic damping prevents oscillation of the upper specimen holder.

The nonlinear spring rate of the diaphragm springs allows a wide range of normal loads, up to 20 pounds, while still maintaining fine control of small loads. The load displacement relationship is shown in Figure 4.

Sample Wear Transducers

The Model A Tribometer includes two transducers that allow dynamic measurement of sample wear as small as 0.01 mils without the removal of the specimen from the Tribometer sample holders. The two transducers for monitoring wear are:

- Hall Effect wear transducer
- Fluidic differential pressure transducer.

These two sensors use different techniques to measure the changes in the relative position of the upper specimen holder, to the lower specimen.

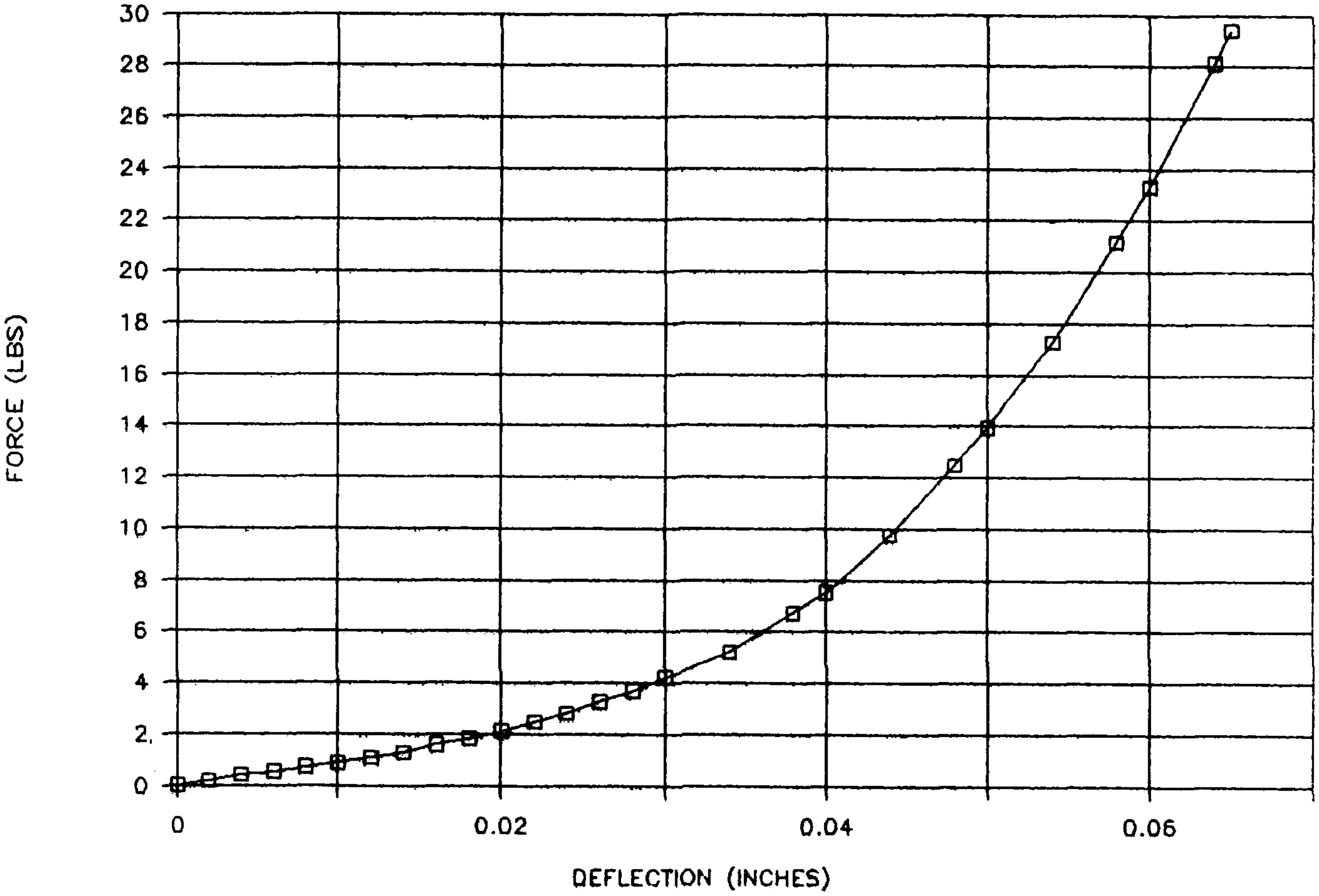


Figure 4. Vertical Load Force versus Spring Displacement

Hall Effect Wear Sensor

The Hall Effect Sensor is a solid state electrical device which is used to accurately measure movement of the upper specimen holder relative to the transducer head housing. The vertical compliance of the diaphragm springs of the sample load system allows the upper specimen to move as the sample wears. The Hall Effect sensor's output changes linearly with this movement. The overall travel of the diaphragm springs is several times the ±.010 inch full scale range of the Hall sensor. However, the sensor can be electrically zeroed anywhere over the diaphragm spring travel with the electronic amplifier in the control box.

Fluidic Wear Transducer

The sensitivity of the Hall Effect Wear Sensor to specimen temperatures led to the inclusion of an additional wear transducer on the High-Temperature Tribometer. It is based upon a fluidic differential pressure transducer which measures the gap between the lower specimen surface and the tip of a sensing nozzle next to the upper specimen. Since it is in close proximity to the specimens, the fluidic sensor is much less sensitive to thermal expansion from large changes in temperature than the Hall Effect Sensor. The fluidic transducer's output is plotted against displacement in Figure 5. A schematic representation of the fluidic system is shown in Figure 6. A design which is insensitive to gas temperature is obtained by having both orifices in the high-temperature zone. The internal orifice D1 is platinum for oxidation resistance and the external orifice is replaceable and made of Kanthal.

Lubrication Feeders

The Model A Tribometer is designed to support two lubrication feeders that automatically inject a controlled amount of lubrication into the test chamber. The two lubrication feeders are:

- Liquid feeder
- Powder feeder.

Accurate control of the lubricant feed rate is provided by a small DC stepper motor attached to each feeder. Both powders and liquids are injected into the test chamber through a port in the upper furnace cover plate.

Liquid Feeder

The liquid feed system utilizes a commercially available valveless positive displacement pump. By adjusting the flow per revolution and the speed of the drive motor liquid lubrication can be fed up to a rate of 15 milliliter per minute in steps of 0.001 milliliter per minute.

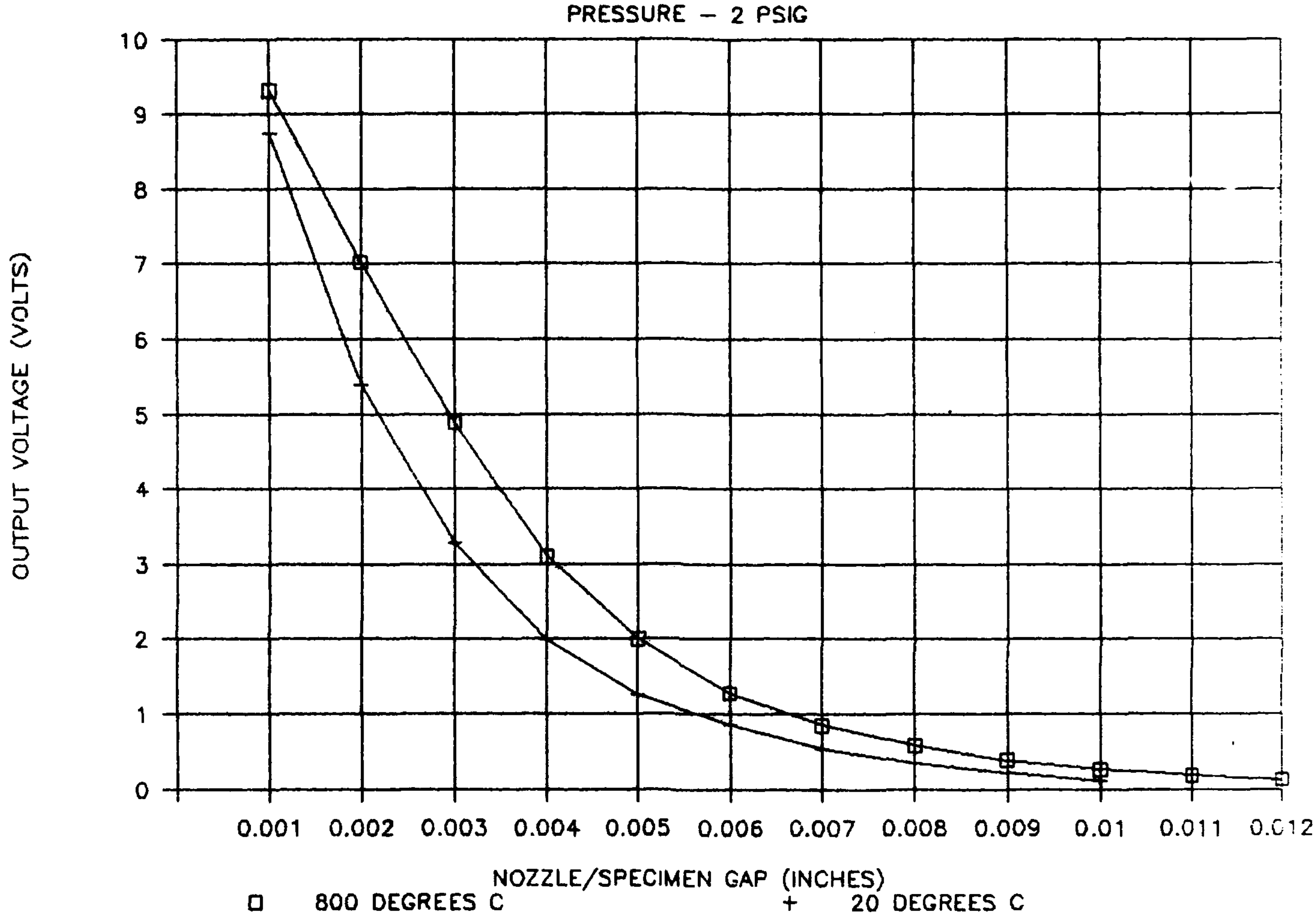
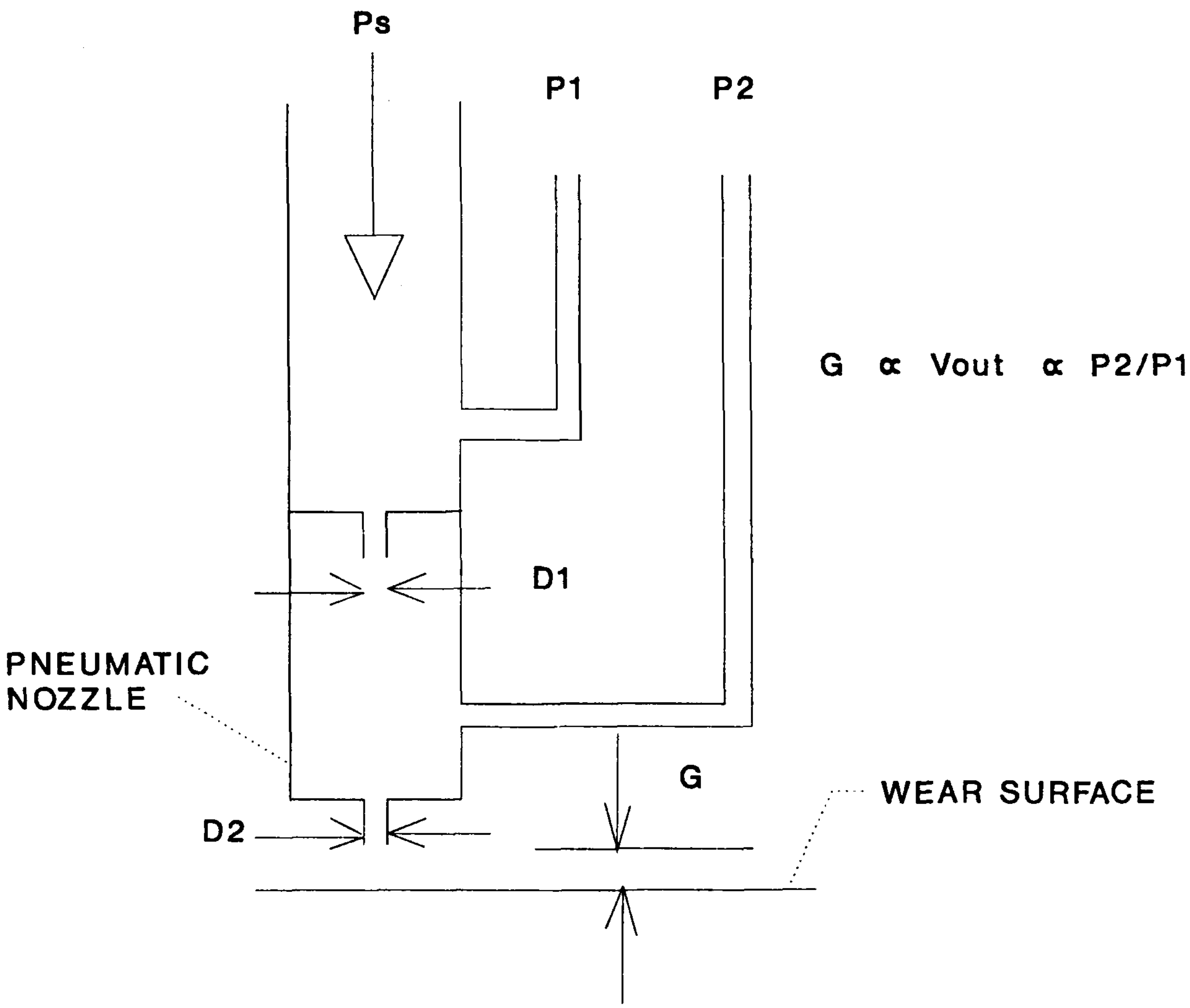


Figure 5. Fluidic Displacement Sensor Output



Ps = Supply Pressure, 2 psig Typical

P1 = Inlet Pressure to Orifice D1

P2 = Inlet Pressure to Orifice D2

D1 = .030 inch Internal Platinum Orifice

D2 = .062 Inch Sensing Nozzle

G = Sensing Gap, < .010 inches

Vout = Output Voltage

Figure 6. Schematic Overview of Fluidic Displacement Sensor

Powder Feeder

AMTI developed the powder feed system for the WL after an extensive development effort. The final design solves many technical problems associated with handling fine powders. It allows the injection of small measured amounts of powdered lubricant at a variable feedrate.

The feeder uses a small reciprocating plunger to inject powder. A steady supply of lubricant is maintained by mechanically fluidizing the powder and allowing it to flow below the plunger before each stroke.

Granular materials will flow down an incline at an angle greater then their angle of repose, but powders will adhere to vertical and even overhead surfaces without falling. Rapid vibration of the feeder overcomes any adhesive properties of a powdered lubricant and the fluidized powder flows toward the plunger.

The control algorithm for the feeder is implemented in software on the Tribometer mother-board. The feedrate can be controlled in steps of 0.1 strokes per minute to a maximum feedrate of 120 stroke per minute. Figure 7 shows an isometric drawing of the feeder.

High-Temperature Furnace Test Chamber

The Model A High-Temperature Tribometer is equipped with a high-temperature furnace test chamber which allows the accurate control of sample temperature up to 1000 degrees Centigrade. The test chamber consists of a special gold reflective insulated furnace. The heater control is interlocked to a chiller system that protects the critical components from damage while the samples are heated.

The sample is loaded into the furnace by raising the Z-axis. The Z-axis raises both the lower sample holder and the furnace test chamber, mating them to the upper specimen holder.

The furnace consists of a pair of concentric quartz cylinders which enclose a high-temperature 3000-watt Kanthal heating element, which are in turn enclosed by a gold film Pyrex mirror. The gold mirror on the inside of the Pyrex cylinder eliminates most radiational heat loss through the glass by reflecting nearly all outgoing infrared radiation back to the center of the furnace.

The top and bottom of the furnace consists of water cooled aluminum end plates. These plates are plated with gold to reflect infrared radiation.

The reflective film furnace used in the Model A has a Kanthal ribbon heating element which operates at low voltage and high current. Earlier tribometers required high-resistance fine wire heating elements in order to operate at 110 volts. These wire elements were horizontally wound and held apart by ceramic spacers. They were difficult to assemble and prone to damage by coil shorting due to thermal expansion. The new ribbon element is wound in a vertical serpentine shape and is self-supporting, easily manufactured and replaced, and is more rugged than the wire element.

1. SLIDING FURNACE COVER PLATE
2. FEEDER BASE
3. RESERVOIR CAP
4. CAM RING BEARING
5. ECCENTRIC CAM FOLLOWER
6. CAM DISK
7. DC STEPPING MOTOR MOUNT
8. DC STEPPER MOTOR
9. COVER PLATE VERTICAL SLIDE SHAFT (2)
10. CONNECTOR
11. POWDER
12. POWDER RESERVOIR
13. VALVE PLUNGER
14. "O" RINGS
15. WAVE SPRING
16. SLEEVE BEARING
17. COVER PLATE ROLLING BEARING (4)
18. DRIVE UNIT MOUNTING SCREW (2)

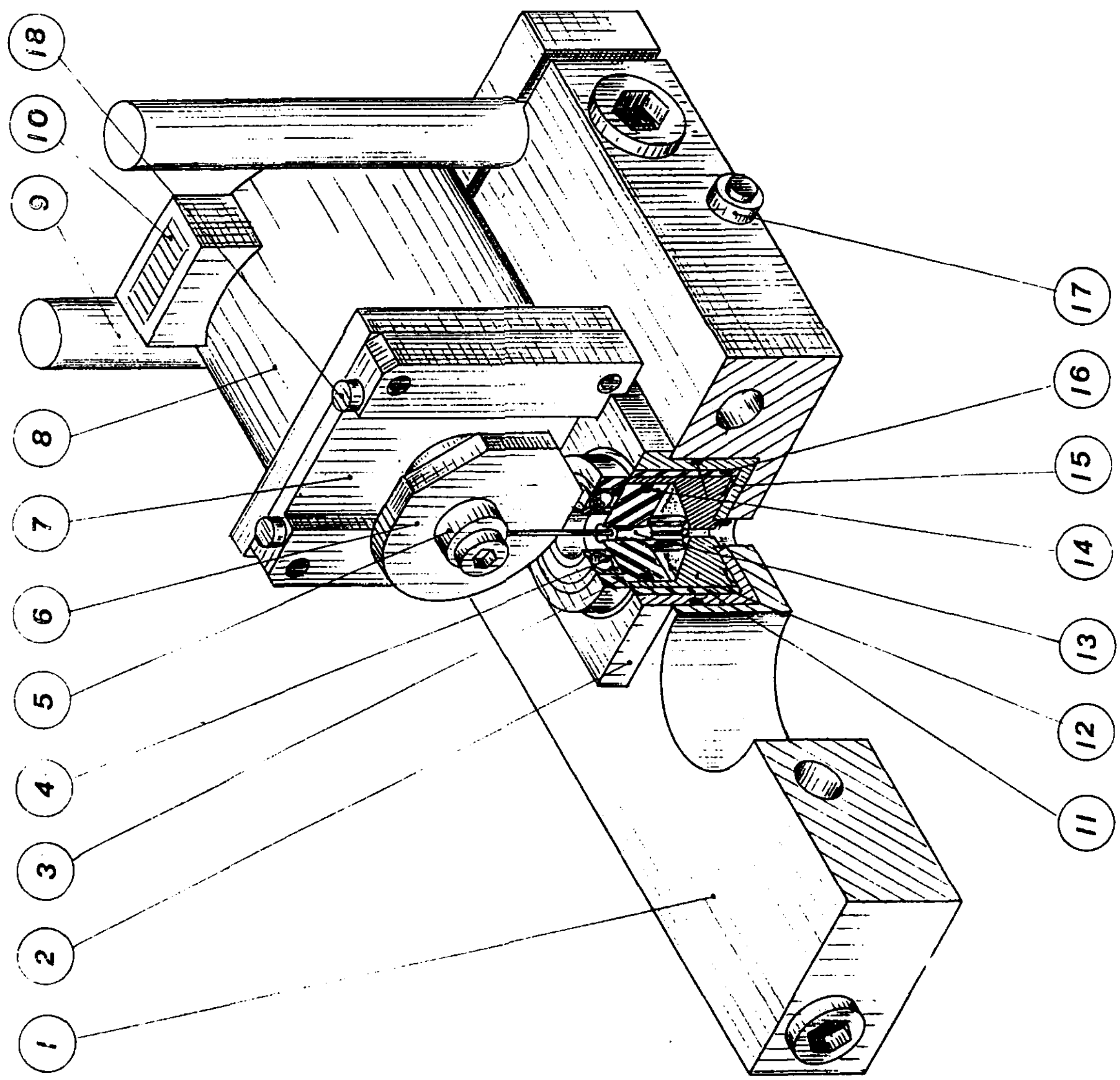


Figure 7. Isometric Drawing of Powder Lubricant Feeder

A special zero voltage switched integral cycle controller was designed and built to provide the high current heater power. This controller was necessary to eliminate magnetic unbalance of the high current transformers and to provide low electrical noise from current spikes.

At room temperature, the furnace is opaque. However, when the furnace is heated, the samples can be seen through the gold film.

A thermocouple is attached to the transducer head. The thermocouple enters the furnace as it is raised by the Z-axis. At the fully closed position, the thermocouple is within 1 inch of the sample and monitors the temperature of the sample test chamber.

Atmospheric Control Chamber

An atmospheric control chamber is provided to allow the testing of friction and wear under a controlled atmosphere.

The atmospheric control chamber consists of a large glass bell jar atop a large stainless steel cylinder. A drive train that raises and lowers the chamber is attached to the back of the cylinder. A rubber gasket at the bottom of the chamber mates it to the precision ground bottom plate.

The atmospheric control chamber can be automatically raised and lowered. As a safety feature a vacuum interlock switch prevents the chamber from being raised when evacuated and a slip clutch limits the maximum force exerted by the drive train.

The atmospheric control chamber allows testing under vacuum. A vacuum pump fitting and valve are provided beneath the Tribometer bottom plate. An additional port is provided for filling the chamber with a non-corrosive test gas.

ELECTRICAL POWER SYSTEM

Electrical power system is contained in the power box attached to the rear of the Tribometer mechanical system. This box contains the power distribution for the entire Tribometer, fuses and relays, various DC power supplies required by the electronic systems, servo amplifiers to control the three DC motors, and the power system for the high-temperature furnace.

CHILLER SYSTEM

The chiller system consists of a recirculating chiller and a mechanical assembly that conducts coolant through telescopic tubing into coolant ducts machined into the furnace end plates, transducer assembly, and other temperature sensitive parts.

Three safety interlocks prevent the operation of the high-temperature furnace without proper operation of the chiller system. A flow switch and a temperature switch sense proper operation of the cooling system, while a relay prevents the heater from being turned on without first turning on the chiller.

ELECTRONIC CONTROL SYSTEM

The electronic control system is a modular system compromised of 10 individual control modules and may be operated in one of two modes:

- Computer control of all functions and support of automatic data logging
- Operate in a stand-alone mode via the individual control modules.

The electronic control system contains a 16-bit microprocessor to support all digital control and the interface to an attached computer. Each control module has an independent front panel display and controls which allow stand-alone operation.

The 10 modules are:

- One microprocessor controller
- Five strain gauge amplifiers
- Three motor controllers
- One heater controller.

These modules are described in the following sections. The front panels of these modules are shown in Figure 8.

Microprocessor Control Panel

The microprocessor control panel provides stand-alone digital control of the Tribometer through a direct interface to the tribometer mother-board. The control panel's 4 line by 40 character LCD display and eight switch keypad allow digital control of the Tribometer and direct access to all sensor outputs.

The control panel is an extension of the microprocessor that controls the Tribometer. When the Tribometer is used as a stand-alone instrument (without an attached computer) the control panel provides direct access to the embedded control program that runs the Tribometer.

Operating the Tribometer using the Control Panel

The LCD display on the microprocessor control panel displays information about the state of the Tribometer and the tasks being performing by the Tribometer. The keypad is used to manipulate the displayed information.

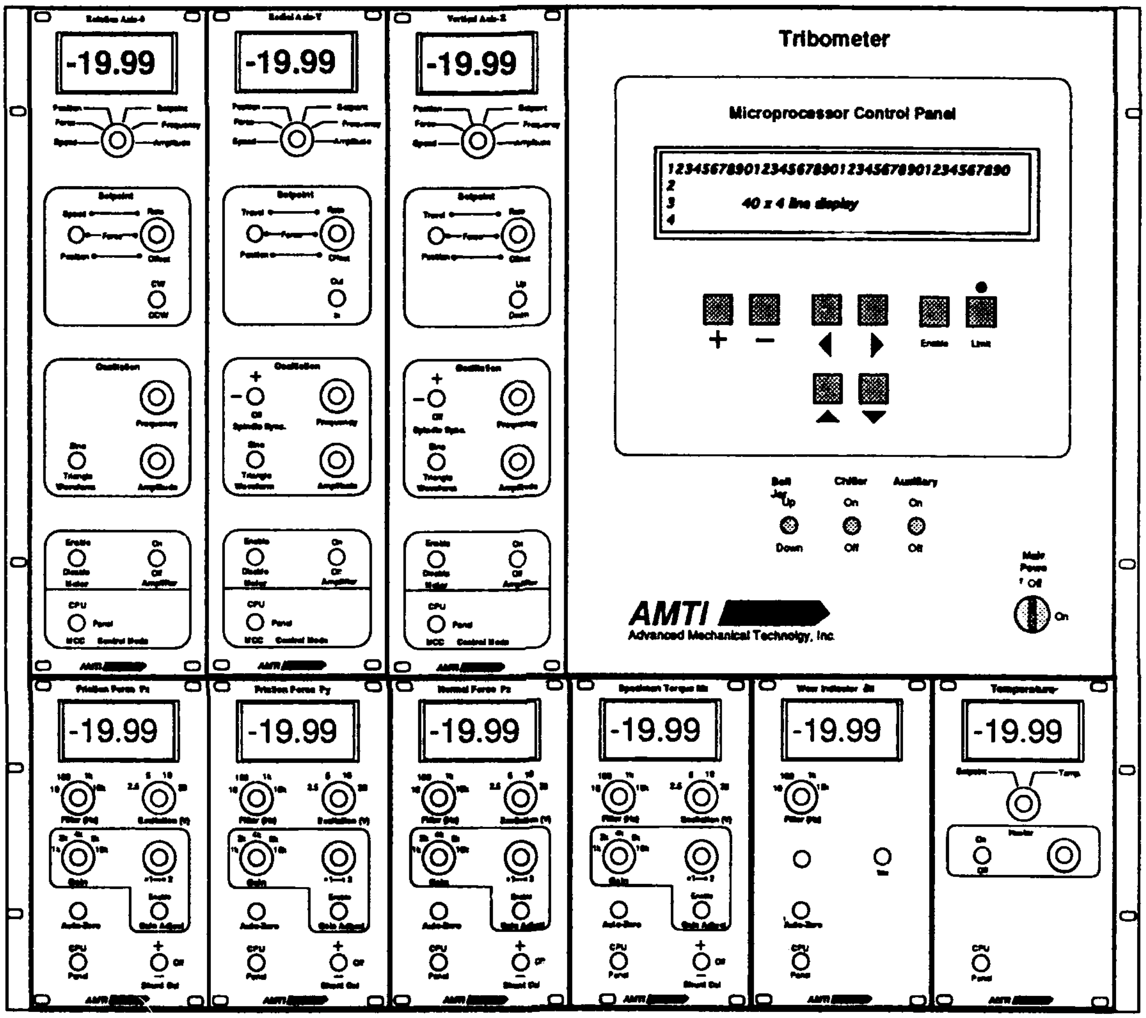


Figure 8. Front Panels of Electronic Control Box

The displayed information is grouped into several menus. The following menus are supported:

- Position control
- Velocity control
- Sample wear monitoring
- Temperature control
- Lubrication feeder control
- Force and friction monitoring.

Strain Gauge Amplifiers

The strain gauge amplifiers condition the strain gauge signals from the multi-axis force transducer. These integrated amplifiers provide controls for the following parameters and functions:

- Strain gauge excitation voltage
- Input filter cut-off frequency
- Signal gain
- Auto-zeroing amplifier output.

These functions can be controlled from an attached computer or the modules' front panel controls. When controlled from a computer the amplifier output are automatically scaled and converted by Tribometer mother board to forces in engineering units.

Motor Control Modules

Three motor control modules provide analog control of the position and velocities of the three axes. These functions are redundant with the digital control provided by the Tribometer mother-board. However, the motor controller performs several functions not provided by the mother board:

- Control of position with force/torque feedback
- Oscillatory motions.

Force/Torque Feedback for Position Control

Force/Torque feedback provides dynamic control of the sample load when positioning the axis. The desired sample load is set with a potentiometer. The motor controller controls the axis position until the desired load matches the output of the appropriate channel of the multi-axis force transducer.

Oscillatory Motions

Each axis' position and load can oscillated at a frequency up to 5 Hertz. Frequency, amplitude and waveform (sine or triangle) of the oscillation are selected by the operator.

Heater Control Module

The heater control module is a zero voltage switching, integral cycle controller. This ensures low electrical noise (the zero voltage crossing part) and prevents magnetic saturation of the power transformers (the integral cycle part). The heater controller controls the temperature by varying the duty cycle (the average power) of the furnace's low voltage, high current AC power source. The heater module allows the optional control of temperature directly from its front panel.

All power systems for the heater are located in the electrical box attached to the Tribometer.

COMPUTER INTERFACE

The most advanced features of the Tribometer are accessed by a robust computer interface. The computer interface controls and monitors all aspects of the Tribometer through a simple set of messages. These messages are communicated over an industry-standard RS-232 serial interface. The mother-board interprets these messages and generates responses.

The Tribometer can be interfaced to any computer programmed to transmit and receive these messages. AMTI, as part of this project, has developed a software interface program that runs on IBM compatible Personal Computers (PCs).

PC Software Interface

The PC's interface program communicates with the Tribometer through a small number of predefined messages. These messages access over 100 Tribometer parameters and initiate various automated procedures. The following control functions are supported:

- Automated collection of time stamped data
- Control of axes
- Control of strain gauge amplifiers
- Control of heater
- Control of lubrication feeders
- Monitoring of the following parameters:
    - sample wear
    - sample load
    - coefficient of friction
    - sample temperature
    - position and speed.

PRESHIPMENT TESTING AND DISCUSSION

The separate subsystems of the High-Temperature Tribometers were each tested before shipping. As a result of these tests, several modifications were made to many parts of the tribometer. Some of these will be described next.

- The reflective film furnace winding was replaced with a higher wattage element in order to reach 1000°C. The furnace losses with the new water cooled ends were higher than previous designs. The original element was 2000 watts; the newer element is 3000 watts.

- All internal lead screw driven slides were fitted with harmonic drive reducers. The machine originally had 5:1 ratio sprocket belt driven reducers between the servo motors and the lead screws. The lead screw torque was insufficient for the positioning performance required. The 80:1 ratio harmonic drives slowed down the maximum slide speed but provided much more controllable Z and Y axis motions.

- The bell jar lead screw drive was fitted with a torque limiting slip clutch to prevent excessive thrust in the event of a limit switch malfunction. This is not a likely occurrence but it was felt worthwhile in order to prevent possible machine damage.

- The main spindle unit bearing assembly was redesigned to eliminate coupling and torque loss problems. The original spindle unit had four preloaded bearings to provide a high thermal conductivity path between the rotating spindle and the water cooled bearing housing. However, too much torque was required by the bearings when lubricated with perflourinated polyether grease. In addition, the backlash free motor coupling failed apparently due to some slight misalignment problems. The spindle was redesigned with only one bearing and the motor shaft was rigidly clamped to the rotary spindle. The thermal conductivity path was made through some .010" annular gaps between the rotating spindle and the housing. This revised design produced an extremely low loss and rigid spindle assembly. The only disadvantage resulting from the large reduction in bearing friction was the reduced spindle damping which made oscillatory spindle motion harder to control.

- The high-temperature pin specimen holder has a spring loaded collet which grips the pin. In previous machines Inconel 625 collets and sleeves with 45° contact angles were used without collet sticking problems. In this machine the contact angle was increased to 70° due to sticking problems which prevented the collet from self-tightening over the entire temperature range. At 45° the friction coefficient must be less than 1 to allow sliding, while at 70° it must be less than 2.75. The 70° collets did not stick and functioned correctly.

- A defective solenoid valve in the recirculating chiller unit prevented it from cycling off and the entire machine would get very cold. The unit was returned to the manufacturer and repaired.

- The lower stainless steel vacuum chamber was not manufactured with flat enough ends to seal against the rubber vacuum gaskets. A large rotating plate with silicon carbide abrasive facing was set up as a lapping machine to flatten the ends. The process, which took about 12 hours, produced very flat surfaces which sealed easily. Using a 4 cfm vacuum pump, evacuation to 100 microns took well under an hour. The system was pumped down to less than 10 microns.

- The electronic control box which includes the microprocessor unit underwent one major circuit board revision to reduce electrical noise. One specific type of integrated circuit chip on this board was unavailable due to chip manufacturing problems which arose after the chip had been designed into the board and samples had been received. This problem lasted for almost 3 months before the parts were supplied.

- The powder feeder was tested with molybdenum disulphide powder and a control algorithm was found which produced consistent feeding. The resulting software algorithm should allow controllable amounts of different powders to be introduced into the test chamber. A calibration should be performed for each powder to determine the actual amount fed per cycle.

CONCLUSION

AMTI developed this High-Temperature Tribometer on Contract F33615-89-C-2971 for the Aero Propulsion and Power Directorate of the Wright Laboratory. The important features of the instrument were tested at AMTI. Each of the specified goals of the program were successfully met. Further work, however, is required to fully realize the potential of the tribometer computer interface. Additional effort spent predominantly on software development would enhance this piece of test equipment.

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